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Calibration of an Orthogonal Cluster of Magnetic Sensors

by Andrew A. Thompson

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1. Introduction

This report demonstrates the use of least-squares estimation as a magnetic sensor calibration procedure. Magnetic sensors are being incorporated into sensor packages to improve attitude estimation of solid bodies. Typically, these units come as an orthogonal triad of single-axis sensors. Each sensor will have a different response to zero input, commonly referred to as the bias, and a different response to excursions from zero, commonly called the scale factor. The simplest model of each sensor is a straight line where the intercept is considered the bias and the slope is interpreted as the scale factor. The ideas are applicable to any type of inner-product measurement and are easily extended past three dimensions.

The manufacture of the triad introduces additional concerns. Misalignment of the sensors will result in a triad that is not quite orthogonal. It is useful to be able to quantify this misalignment. Another problem often confounded with misalignment is cross-axis sensitivity. This can be thought of as the response of a sensor to energy orthogonal to its sensitive axis; or perhaps even to changes in energy orthogonal to its sensitive direction.

Calibration is undertaken to quantify as many of the issues associated with sensor performance as possible. The primary goal is to find the parameters that describe sensor performance, usually bias and scale factor. In addition to this, it is desirable to understand the parameters associated with the sensing unit: misalignment and cross-axis sensitivity.

2. Least Squares

Least squares is a criterion used to optimize the choice of parameters in an over-determined system of equations. The basic equation is formulated as

$$Y = Xb\,, \tag{1}$$

where Y is a vector of measured responses, X is a matrix of known dependent values, and b is a vector relating the dependent values to the response, also called the parameters. It is assumed that X and Y are known through measurement or observation and b is the unknown vector. To solve this matrix equation, there must be at least as many equations as unknowns (rows as columns). If the basic equation provides the correct model of the physical event and there is no measurement noise, the vector b could be found without error. A number of approaches to solve this equation have been presented. If the number of unknowns and equations is the same, the problem is solvable if X has an inverse. An inverse will exist if the inputs associated with each parameter are different or the columns are linearly independent. When more equations exist than

unknowns, the system is said to be overdetermined. For an overdetermined system of equations, the inverse of X does not exist. From an algebraic viewpoint, we would like to perform an operation to both sides of the equation that will allow a solution. Multiplying each side of the equation by the transpose of X leads to the solution. This operation can be interpreted as the projection of each side of the equation into the space spanned by the columns of X; in this sense, only the left side is actually altered. If the columns of X are independent, the solution is

$$b = (X'X)^{-1} X'Y \,. \tag{2}$$

3. Calibration Errors

The accuracy of a calibration is directly related to the fidelity of the equipment. For the calibration of magnetic sensors, a Helmholtz coil is typically used to generate the desired magnetic field orientation that is presented to the sensor. Many systems include a calibrated set of magnetometers to measure the applied magnetic field.

During calibration, there are many potential sources of error. The local magnetic field must be precisely measured. The local field is not constant and any error in its measurement will create a bias in the data. Drift in the local magnetic field will cause a time-varying source of error. Errors in the construction of the Helmholtz coil can be approximated. For example, a 0.5-in error in the placement of a winding over a 5-ft distance results in 0.4775° of orientation error. An error of 0.1 in leads to an orientation error of 0.0955°.

Some of the error sources will be constant over all calibrations, while others may be constant over a given calibration, and some will vary during a calibration. Errors that do not change during a calibration create a bias in the measurements. Taking repeated measurements reduces the influence of errors that change between samples.

4. Calibration

By observing a magnetometer's output to a known input, a mapping can be found. Typically, this mapping is required to have a specific functional form, i.e., the mapping must be a straight line. The response of the magnetometer can be conceived of as the inner product between the presented magnetic field and the normalized direction of the magnetometer's sensitive axis. For an orthogonal triad of sensors, calibration can find the response and orientation of each sensor based on its outputs to known input fields. Ideally, the response of the sensor is just the inner

product and can be represented as

$$y_i = d_1 m_{i1} + d_2 m_{i2} + d_3 m_{i3}, \tag{3}$$

where d is the direction of the sensor and m is the magnetic field. For a typical measurement, the sensor response has a bias or zero offset and a scale factor or response level. Incorporating these factors in the measurement equation leads to the following equation for a measurement:

$$y_i = s(d_1 m_{i1} + d_2 m_{i2} + d_3 m_{i3}) + z, \tag{4}$$

where s is the scale factor and z is the bias or zero offset. A set of measurements can be put into the form needed for least squares estimation.

$$Y = \begin{bmatrix} y_1 \\ \\ y_i \end{bmatrix} \qquad X = \begin{bmatrix} 1 & m_{11} & m_{12} & m_{13} \\ \\ 1 & m_{i1} & m_{i2} & m_{i3} \end{bmatrix} \qquad b = \begin{bmatrix} z \\ sd_1 \\ sd_2 \\ sd_3 \end{bmatrix}. \tag{5}$$

The vector Y is the output from the sensor, the matrix X is the known input (the 1 column is for the zero offset), and the b vector is the set of parameters to be estimated. After parameters are estimated, the scale factor s can be found as the norm of the last three parameters. The direction can be normalized and compared to the direction of other sensors in the orthogonal triad. Using three estimated directions, the misalignment can be estimated. After accounting for misalignment, cross-axis sensitivity can be investigated.

5. The Measurement Matrix, X

The measurement matrix is the matrix of known magnetic fields applied by the Helmholtz coil during the calibration process. The proper selection of this matrix leads to increased accuracy in the parameters estimated. There are three pairs of coils that make a Helmholtz coil; these pairs are orthogonal. Controlling the current flow through each pair of coils generates a known magnetic field.

It is desirable that new measurements add as much information as possible. There are analytic methods based on the measurement matrix that can be applied. First, consider the set of directions generated by each pair of coils when the other two pairs are held to their zero levels. There are two possible directions; this yields six directions of interest. Similarly, two pairs of coils generating equal fields will generate four directions; since there are three distinct pairs, this makes 12 directions. Finally, consider all pairs of coils generating equal strength fields. In Cartesian space, each of these directions has coordinates (1,1,1) where any of the elements can be negative. This gives an additional eight directions. This set of 26 measurements gives

information from each coil, each pair of coils, and all three coils in unison. Normalizing each of these directions provides a set of measurement directions. Multiplying this set by various magnitudes can generate a set of calibration measurements. Different magnitudes allow the linearity of the scale factor to be evaluated.

It is important to randomize the order of the measurements used during calibration. Randomization is used to diminish the effects of unmeasured factors. These could include temperature, changes in the local magnetic field, shifts in electronic parameters, and other possible influences. It is important not to have a measured effect correlated with an unmeasured variable. Appendix A is an example of code that will randomize the test order.

The magnetic field vector generated by the Helmholtz coil defines each measurement. If a calibrated magnetometer is also available, it may be more accurate than the known voltages applied to the coils as a measure of the magnetic field. The two should be in close agreement but there may be a reason to prefer one when forming the measurement matrix. One way to resolve this question is to examine the residual sum of squares resulting from the fit using each as the measurement matrix.

6. Applications

Data was collected in January of 2003 for a three-axis magnetometer-sensing unit. There are five data sets available; they are included in appendix B. The largest two include 104 observations, there are two sets containing 26 observations, and one set of eight observations. Each data set contains nine columns (C1-C9); the first three are the intended magnetic field based on the inputs to the coils, the next three are the coil's calibrated magnetometer readings, and the final three are the outputs of the magnetometer to be calibrated. The results of least-squares estimation is presented and discussed for each data set.

6.1 Data Set 1

This data set consisted of eight observations, two at the zero level and then at values of ±0.5 gauss using each pair of coils for six more observations. Table 1 contains the estimates of each sensor's bias and direction. The scale factor is easily found as the norm of the direction.

Table 1. Parameter estimates based on input values.

Data Set 1	Parameters Based on C1-C3			
	Bias	d_1	d_2	d_3
Sensor 1	2.8068	–0.0296	1.9575	–0.1016
Sensor 2	2.5309	–1.8119	–0.0287	–0.0185
Sensor 3	2.5652	0.0235	–0.0582	–2.0397

Table 2 contains an analysis similar to that of table 1, the difference is that the measurement matrix is based on the output of a calibrated magnetometer rather than the intended inputs. Comparison of the two tables shows agreement; however, the variability of the estimates needs to be quantified.

Table 2. Parameter estimates based on probe measurements.

Data Set 1	Parameters Based on C4-C6			
	Bias	d_1	d_2	d_3
Sensor 1	2.7989	–0.0504	1.9619	–0.0789
Sensor 2	2.5280	–1.8124	–0.0180	–0.0502
Sensor 3	2.5861	–0.01120	–0.0855	–2.0406

The covariance matrix associated with a least squares estimate can be used to quantify the variability of each component of the estimate. Another useful measure is the residual sum of squares (RSS). The RSS can be used to estimate the measurement error. Table 3 contains the RSS for each sensor. The sensor model associated with table 1 will be called model 1; model 2 will be based on table 2.

Table 3. Comparison of residuals for the input and probe dependant variables.

RSS of Model	Model 1	Model 2
Sensor 1	5.570 e-4	4.751 e-4
Sensor 2	6.725 e-4	6.953 e-4
Sensor 3	4.067 e-4	3.878 e-4

For this set of data, it appears that using the calibrated magnetometer as the measurement matrix reduces the RSS; however, the difference between the two may not be significant statistically. An estimate of the variance of the observations can be found by dividing the RSS by the result of subtracting the number of estimated parameters from the total number of observations. For this case, observation variance is the value in table 3 divided by 4.

Once the observation variance is known, the variance of the estimated parameters can be discussed. The inverse measurement matrix, $(X^{'}X)^{-1}$, multiplied by the observation variance gives the variance of the estimated parameters. For the two measurement matrices, these inverse matrices are given in table 4. Model 1 has a simple structure; while the off-diagonal elements in model 2 make the interpretation more involved. The off-diagonal elements indicate the parameters are correlated. The variance of the bias for sensor 1 in model 1 can be found by dividing the RSS by 4 and then multiplying by 0.125; the bias variance for the other two sensors can be found similarly. The variance for each term of the direction can be found by doubling the observation error for the particular sensor. Variances of linear quantities derived from the elements of the direction can be found or approximated given the variances of the estimated quantities.

Table 4. Observation matrix for input and probe models.

Model 1				Model 2			
0.1250	0	0	0	0.1253	0.0033	–0.0093	–0.0203
0	2.0000	0	0	0.0033	2.017	–0.0313	0.0689
0	0	2.0000	0	–0.0093	–0.0313	2.0118	0.0501
0	0	0	2.0000	–0.0203	0.0689	0.0501	2.0021

Consider trying to decide which measurement matrix is more appropriate. The RSS for each model is available. Assuming normally distributed errors each of the RSS is a chi square random variable with 4 degrees of freedom (DOF). Since each model has the same DOF, taking the ratio of two chi square variables forms the F distribution. This ratio would have to be <0.157 or >6.39 to exceed the thresholds of 0.1 significance test; obviously, there is no basis for saying one model is better than the other. The interval of statistically similar ratios is large; the way to decrease this interval is to increase the number of observations. For 120 DOF in each RSS, the interval would be from 0.740 to 1.35. For this small set of observations, it will be difficult to discern statistically between competing models.

The bounds for the bias have already been discussed. The estimate of direction has a trivariate normal distribution. The chi square distribution can be used to find the probability that the actual direction is within a sphere of a given radius. Denoting the errors with e the following statement describes the sum of three independent squared normal errors:

$$p\left(0 \le \frac{e_1^2}{\sigma^2} + \frac{e_2^2}{\sigma^2} + \frac{e_3^2}{\sigma^2} < \chi^2(3,\alpha)\right) < 1-\alpha \,. \tag{6}$$

Using r as the error magnitude, the equation within the parenthesis can be transformed to the following statement:

$$p\left(0 \le r < \sigma\sqrt{\chi^2(3,\alpha)}\right) < 1-\alpha \,. \tag{7}$$

The chi-squared value is fixed for a given probability level, so the radius depends on the estimation error, which is a function of the measurement error and measurement matrix (table 5).

Table 5. Percentiles for square roots of chi square with 3 DOF.

1-α	**0.25**	**0.5**	**0.7**	**0.75**	**0.8**	**0.9**	**0.95**	**0.99**	**0.999**
$\sqrt{\chi^2(3,\alpha)}$	1.1012	1.5382	1.9144	2.0269	2.1544	2.5003	2.7955	3.3682	4.0331

This table gives the values to multiply the standard deviation by to attain the indicated probability for a sphere containing the true direction. Applying this to sensor 1 using model 1, we have an estimated direction of (–0.0296, 1.9575, –0.1016). The norm of the estimate is 1.9604. The RSS value of 0.000557 is divided by 4 to obtain the observation variance; the result is 0.00013925. The estimate variance is the product of the observation variance and the inverse measurement matrix. This gives the estimate variance of 0.0002785; taking the square root results in a standard deviation of 0.0167. A sphere with a radius of 0.0562 will contain the true direction (and scale factor) with a probability of 0.99.

Errors perpendicular to the estimated direction result in angular errors while errors in the same direction change the scale factor. Using the norm value of 1.9604, the maximum angular error for a sphere with a radius of 0.0562 would be 1.642°, and the norm error would be 2.87%. Similarly, for sensor 2 and sensor 3, the difference is the measurement variance. For a 0.99 sphere, similar calculations result in deviations of 1.9480° and 3.4% in the norm for the estimate of sensor 2. Similarly, for sensor 3, the angular deviation is 1.3483° and the norm changes by 2.35%. The spherical radius gives the engineer a basis for discussing the fidelity of a sensor calibration.

The discussion of the precision of a sensor is enhanced by considering some marginal distributions. Errors in the scale factor are confined to a single dimension. The scale-factor errors will have a normal distribution; confidence intervals on the scale factor can be set based on the normal distribution. For a 99% confidence interval, the critical value is 2.575 resulting in radius or half interval of 0.043. This value is smaller than the radius given for the three-dimensional radius because there are no restrictions on the angular error. Angular confidence limits can be set using the chi-squared distribution with two degrees of freedom. The square root of the chi-squared value for 99% confidence is 3.0349 (table 6 shows the values).

Table 6. Percentiles for square root of chi square with 2 DOF.

$1-\alpha$	**0.25**	**0.5**	**0.7**	**0.75**	**0.8**	**0.9**	**0.95**	**0.99**	**0.999**
$\sqrt{\chi^2(2,\alpha)}$	0.7585	1.1774	1.5518	1.6651	1.7941	2.1460	2.4477	3.0349	3.7169

Multiplying this by the standard deviation yields 0.0507. Using the norm of a sensor and the arctan function, the angular error can be found. For sensor 1, this yields 1.4815°. Recall the observation error changes for each sensor. For sensor 2, the process yields 1.7589° and for sensor 3, the result is 1.2149°.

The next issue is the relative orientation of the sensors. The manufacturing process attempts to produce an orthogonal triad of sensors. Some issues associated with misalignment are discussed. First, each of the sensor directions needs to be normalized. The next step is to compute the inner

product matrix of the sensor directions. The off-diagonal components indicate a departure from orthogonality. Taking the arccosine of these values yields the angle between the sensors. Performing this operation results in 90.0108° between sensor 1 (S1) and sensor 2 (S2), 88.6735° between S1 and S3, and 90.0492° between S2 and S3. In view of the previous discussion of angular deviation for each individual sensor, there is not enough fidelity to say any of these angles is statistically different from 90°.

The discussion of the data just completed is redone for the remaining data sets; however, the discussion will not provide the same level of detail and will focus on comparative issues when pertinent.

6.2 Application 2

The second data set contained 26 observations. The least squares using data set 2, columns 1–3 (C1–C3), resulted in smaller values of RSS for each model; the results using columns 4–6 of data set 2 will not be shown. Table 7 shows the results of the least squares fit.

Table 7. Estimates based on data set 2.

Parameters Based on C1-C3					
Data Set 2	**Bias**	**D1**	**D2**	**D3**	**RSS**
Sensor 1	2.8131	–0.0173	1.9238	–0.0880	0.0037
Sensor 2	2.5113	–1.7835	0.0105	–0.0181	0.0025
Sensor 3	2.6036	0.0213	–0.0761	–1.9997	0.0047

The covariance matrix of the parameters is determined by dividing the appropriate RSS value by 26–4 = 22, and then multiplying that value by the following matrix (table 8).

Table 8. Covariance matrix for data set 2.

Inverse Measurement Matrix $(X'X)^{-1}$			
0.0385	0	0	0
0	0.1154	0	0
0	0	0.1154	0
0	0	0	0.1154

Table 9 uses values from the previous two tables. The standard deviations of the parameters define the resolution of the calibration. Using these values, probability statements can be made.

Table 9. Parameter standard deviation for data set 2.

Standard Deviation of Parameter				
Data Set 2	**Bias**	**D1**	**D2**	**D3**
Sensor 1	0.0025	0.0044	0.0044	0.0044
Sensor 2	0.0021	0.0036	0.0036	0.0036
Sensor 3	0.0029	0.0050	0.0050	0.0050

Table 10 gives the radius for 99% coverage of the true value. The bias and scale factor are one-dimensional. The 99% angular error can be found using the circular radius. The tangent of this angle is the circular radius over the norm of the estimated direction.

Table 10. The 99% probability radius for estimates of data set 2.

0.99 Probability Radius				
Data Set 2	**Bias**	**Scale Factor**	**Circular**	**Sphere**
Sensor 1	0.0064	0.0113	0.0134	0.0148
Sensor 2	0.0054	0.0093	0.0109	0.0121
Sensor 3	0.0075	0.0129	0.0152	0.0168

The 0.99 angular cone for sensor 1 has an angle of 0.3986°; for sensor 2, it is 0.3501°; and for sensor 3, this cone is 0.4352°. The angles between sensor axes are calculated as 89.1209 between S1 and S2, 89.5668 between S1 and S3, finally 90.0409 between S2 and S3. In this case, there is statistically significant misalignment, since some differences exceed the 0.99 angular error cones. Note that the 0.99 confidence interval reflects a conservative outlook.

6.3 Application 3

In this section, the results are presented in chart form (tables 11–13); hopefully, in light of the former discussion, these will suffice. There are 26 observations.

Table 11. Estimates for data set 3.

Parameters Based on C1-C3					
Data Set 3	**Bias**	**D1**	**D2**	**D3**	**RSS**
Sensor 1	2.8027	–0.0232	1.9191	–0.0856	0.0041
Sensor 2	2.5320	–1.7804	0.0081	0.0105	0.0026
Sensor 3	2.5630	–0.0094	–0.0748	–1.9976	0.0049

Table 12. Parameter standard deviation for data set 3.

Standard Deviation of Parameter				
Data Set 3	**Bias**	**Scale Factor**	**Circular**	**Sphere**
Sensor 1	0.0027	0.0046	0.0046	0.0046
Sensor 2	0.0021	0.0037	0.0037	0.0037
Sensor 3	0.0029	0.0051	0.0051	0.0051

Table 13. The 99% probability radius for data set 3.

0.99 Probability Radius				
Data Set 3	**Bias**	**Scale Factor**	**Circular**	**Sphere**
Sensor 1	0.0070	0.0118	0.0140	0.0155
Sensor 2	0.0054	0.0095	0.0112	0.0125
Sensor 3	0.0075	0.0131	0.0155	0.0172

The 99% angular error for each sensor axis (in degrees) is 0.4175, 0.3604, and 0.4528. Estimated angles between axes are 89.0627 between S1 and S2, 89.5873 between S1 and S3, and 90.0780 between S2 and S3. Happily, these results are similar to the previous results.

6.4 Application 4

This data set contains 104 observations or four replications of the previous data set at four different field strengths (presented in random order of course). The data is presented in the previously developed format (tables 14–16).

Table 14. Estimates of data set 4.

Parameters Based on C1-C3					
Data Set 4	**Bias**	**D1**	**D2**	**D3**	**RSS**
Sensor 1	2.8016	–0.0165	–1.9427	0.0954	0.0097
Sensor 2	2.5077	1.7762	0.0177	–0.0200	0.0080
Sensor 3	2.6054	–0.0373	–0.0743	–2.0019	0.0081

Table 15. Standard deviation of estimates for data set 4.

Standard Deviation of Parameter				
Data Set 4	**Bias**	**D1**	**D2**	**D3**
Sensor 1	9.650 e-4	0.0037	0.0037	0.0037
Sensor 2	8.764 e-4	0.0033	0.0033	0.0033
Sensor 3	8.818 e-4	0.0033	0.0033	0.0033

Table 16. Probability radius for data set 4.

0.99 Probability Radius				
Data Set 4	**Bias**	**Scale Factor**	**Circular**	**Sphere**
Sensor 1	0.0025	0.0094	0.0111	0.0123
Sensor 2	0.0023	0.0085	0.0101	0.0112
Sensor 3	0.0023	0.0086	0.0101	0.0112

The respective 99% errors associated with each sensor axis are 0.327, 0.3258, and 0.2888°. The angles between axes are estimated to be 88.912, 89.3234, and 90.4432 are denoted as S12, S13, and S23. In this case, all the angles are statistically different from 90.

6.5 Application 5

This data set is a replication of data set 4 (tables 17–19).

Table 17. Parameter estimates for data set 5.

Parameters Based on C1-C3					
Data Set 5	**Bias**	**D1**	**D2**	**D3**	**RSS**
Sensor 1	2.7911	0.0211	1.9398	0.0922	0.0093
Sensor 2	2.5302	1.7740	0.0123	0.0057	0.0099
Sensor 3	2.5646	0.0087	0.0730	1.9988	0.0100

Table 18. Standard deviation of parameters of data set 5.

Standard Deviation of Parameter				
Data Set 5	**Bias**	**D1**	**D2**	**D3**
Sensor 1	9.449 e-4	0.0036	0.0036	0.0036
Sensor 2	9.749 e-4	0.0037	0.0037	0.0037
Sensor 3	9.798 e-4	0.0037	0.0037	0.0037

Table 19. The 99% probability radius for data set 5.

0.99 Probability Radius				
Data Set 5	**Bias**	**Scale Factor**	**Circular**	**Sphere**
Sensor 1	0.0024	0.0092	0.0108	0.0120
Sensor 2	0.0025	0.0095	0.0112	0.0124
Sensor 3	0.0025	0.0095	0.0112	0.0125

The 99% angular error is 0.3201 for S1; for S2, it is 0.3615; and for S3, it is 0.3222. The angles between sensor axes are estimated as 88.989, 89.3731, and 90.4477.

7. Discussion of Results

Each of the data sets was generated using the same sensing unit. The estimates based on the fourth and fifth data sets will be discussed. First, note that the RSS is the unique factor in calculating the standard deviation of each estimate. Also note that the bias estimates differ from a statistical perspective. Table 20 displays the 99% confidence intervals of the estimates of the bias. The intervals do not overlap.

Table 20. The 99% confidence intervals of the estimates of the bias.

99% Bias Interval	Sensor 1		Sensor 2		Sensor 3	
	Low	**High**	**Low**	**High**	**Low**	**High**
Data 4	2.7991	2.8041	2.5054	2.5100	2.6031	2.6077
Data 5	2.7887	2.7935	2.5277	2.5327	2.5621	2.5671

All three bias estimates for the same sensing unit differ from a statistical perspective. Although it is possible that these three differences are due to chance, there is a statistical difference between data set 4 and data set 5 at the $\alpha = 0.01$ level of significance. Perhaps the testing equipment has changed or there is a shortcoming in the modeling of bias. If the difference in the bias estimates is important from an engineering perspective, this discrepancy should be investigated.

If the 99% confidence intervals are compared for the direction components (D1, D2, and D3), it can be concluded that the vectors were not pointed in the same direction during testing. The orientation of the sensors with respect to a given coordinate system can change; however, the angles between the sensors in a given unit and the scale factor should be constant. The estimates for the scale factor for data set 4 are (1.9451, 1.7764, 2.0002); for data set 5 the scale factor estimates are (1.9421, 1.7741, 2.0036). These estimates are about one standard deviation unit apart; statistically they are indistinguishable. The estimated angles between the sensors are not significantly different from a statistical perspective. The angular measures all agree to the first decimal point and the 99% radius is on the order of 0.3.

8. Misalignment

The assumed alignment of the sensors determines how each sensor's responses are interpreted. Misalignment leads to errors in orientation and magnitude. The cross-axis effect of misalignment is best understood by considering a series of situations. First, consider the two-dimensional case. Let sensor X be aligned with the X-axis, and let sensor Y be oriented 89° toward the positive Y-axis. If the true signal of strength 1 is along the X-axis, it will be measured as (1*cos(0), 1*cos(89)) or (1,.0175). If the sensors are thought to be orthogonal, this results in an error in magnitude of 0.0002 and a 1° error in orientation of the signal. Next, consider the case where the signal is 45° from the X-axis, sensor X is rotated 0.5° towards the Y-axis, and sensor Y is rotated 0.5° towards the X-axis. The sensors will read (1*cos(44.5), 1*cos(44.5)) or (0.7133, 0.7133). In this case, there is no orientation error; the magnitude error is 0.0088. These two situations illustrate the planar errors due to misalignment. With these ideas, the reader is encouraged to consider misalignment in three dimensions.

A two-phase process can be used to define an orthogonal input given the misalignment is known. First, use a Gram-Schmidt process to form a set of orthogonal vectors. This orthogonal set can then be rotated to a desired coordinate system.

9. Conclusions

The RSS was used to answer several different problems. To compare different models, the ratio of the RSS from each model was used as a statistic. Also, the RSS was used to estimate the measurement variance. The RSS was the basic quantity used to answer a variety of questions.

The procedure demonstrated can be applied to any inner product type of sensor element to calibrate a single sensor or multisensor unit. The accuracy of the estimates can be quantified. In addition to scale factor and bias, the within-unit alignment and the alignment to a given coordinate system can be estimated. The measurement matrix directly affects the estimation error. When designing a calibration the key element is the measurement matrix. The estimation error determines the overall quality of the calibration. If the accuracy required for an application is known, the calibration can be designed to meet the tolerances by using historic RSS values and designing the measurement matrix.

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Appendix A. Example of Code

This appendix appears in its original form, without editorial change.

A program to randomize the test order. See the program comments for further information

```
function y=testorder(strength,n)
%y=testorder(strength,n)
%this function returns a randomized test order
%the test matrix consists of
%the main axis both directions
% the vector between each pair of axis both plus and minus
% the vector of equal magnitudes along each axis plus and minus
%n=1 for normalized
%n=0 for 0 1 representation

v6=[1,0,0;0,1,0;0,0,1];
v6=[v6;-v6];
c1=[1;-1;1;-1];
c2=[1;1;-1;-1];
c3=[0;0;0;0];
c4=[1;1;1;1];

v4=[c2,c1];
v8=[c4,v4;-c4,v4];

v12=[c3,v4;c2,c3,c1;v4,c3];
if n==1
   v8=v8/sqrt(3);
   v12=v12/sqrt(2);
end

testmatrix=[v6;v8;v12];

[sr,sc]=size(strength);
sn=max(sr,sc);
if sn>1
   t=[];
   for i=1:sn
      t=[t;strength(i)*testmatrix];
   end
   testmatrix=t;
end


[r,c]=size(testmatrix);
testorder=[];
for i=1:r
   maxval=r+1-i;
   choice=ceil(maxval*rand);
   testorder=[testorder;testmatrix(choice,:)];
   testmatrix(choice,:)=[];
end
y=testorder;
```

Appendix B. Data Sets

This appendix appears in its original form, without editorial change.

Columns 1-3 are the intended magnetic field
Columns 4-6 are the magnetic field as measured by a sensor
Columns 7-9 are the responses of the sensors being investigated

Data Set 1

0.00000	0.00000	0.00000	-0.00159	0.00213	0.00967	2.79625	2.52097	2.57007
-0.50000	0.00000	0.00000	-0.50191	-0.00116	0.01895	2.82034	3.45084	2.54165
0.50000	0.00000	0.00000	0.49822	0.00875	0.00155	2.79070	1.63893	2.56512
0.00000	-0.50000	0.00000	-0.00501	-0.49421	0.01677	1.83982	2.54762	2.60121
0.00000	0.50000	0.00000	0.00131	0.50317	0.00347	3.79730	2.51896	2.54299
0.00000	0.00000	-0.50000	0.00657	0.01193	-0.48994	2.85863	2.53274	3.58638
0.00000	0.00000	0.50000	-0.01081	-0.00010	0.51022	2.75699	2.51423	1.54667
0.00000	0.00000	0.00000	-0.00240	0.00432	0.01008	2.79400	2.52307	2.56746

Data Set 2

0.00000	0.00000	-1.00000	0.02776	0.02684	-0.97638	2.90067	2.53058	4.57998
0.70711	-0.70711	0.00000	0.71249	-0.69020	-0.01033	1.44828	1.23429	2.68638
0.00000	0.70711	0.70711	0.00279	0.71141	0.69038	4.12489	2.50572	1.14050
0.00000	-0.70711	0.70711	-0.00713	-0.70055	0.71004	1.39752	2.47516	1.23887
0.57735	0.57735	0.57735	0.58114	0.58595	0.55216	3.88222	1.48149	1.41262
-0.57735	-0.57735	-0.57735	-0.56069	-0.55888	-0.56634	1.76549	3.55544	3.82313
-0.70711	0.70711	0.00000	-0.69176	0.71571	-0.00347	4.19132	3.75687	2.52780
0.57735	-0.57735	0.57735	0.57321	-0.56725	0.56739	1.64158	1.45992	1.49480
0.00000	-0.70711	-0.70711	0.01798	-0.68633	-0.70484	1.52501	2.52391	4.06817
0.57735	-0.57735	-0.57735	0.59413	-0.55489	-0.58779	1.73915	1.48168	3.81113
0.70711	0.00000	0.70711	0.70438	0.00510	0.68731	2.71851	1.23633	1.19090
0.70711	0.00000	-0.70711	0.72965	0.02235	-0.72737	2.85654	1.25587	4.01055
0.57735	0.57735	-0.57735	0.60196	0.59444	-0.60253	3.97789	1.51357	3.72400
-0.57735	0.57735	0.57735	-0.57300	0.57101	0.57312	3.89980	3.53698	1.39051
0.00000	0.70711	-0.70711	0.02811	0.72538	-0.72407	4.22275	2.51980	3.96392
0.70711	0.70711	0.00000	0.72185	0.72153	-0.02971	4.16585	1.27200	2.57865
-1.00000	0.00000	0.00000	-0.98885	0.00151	0.01124	2.81475	4.29433	2.57158
0.00000	-1.00000	0.00000	0.00337	-0.95434	0.00663	0.90045	2.49425	2.68612
-0.57735	-0.57735	0.57735	-0.58165	-0.57838	0.58925	1.66239	3.54444	1.49038
-0.57735	0.57735	-0.57735	-0.55349	0.59517	-0.58188	3.99470	3.55273	3.71317
-0.70711	0.00000	-0.70711	-0.68410	0.01643	-0.70152	2.86934	3.78770	4.01504
0.00000	0.00000	1.00000	-0.00811	-0.00401	0.98010	2.70328	2.48635	0.60887
-0.70711	-0.70711	0.00000	-0.70064	-0.70049	0.01557	1.47444	3.76389	2.61663
0.00000	1.00000	0.00000	0.01721	0.97216	-0.02024	4.72995	2.51972	2.52738
1.00000	0.00000	0.00000	0.99992	0.01694	-0.02510	2.78116	0.73389	2.64741
-0.70711	0.00000	0.70711	-0.70882	-0.00073	0.71367	2.75260	3.77634	1.17392

Data Set 3

0.00000	0.00000	-1.00000	0.01556	0.01357	-0.95656	2.88866	2.52042	4.53917
0.70711	-0.70711	0.00000	0.70023	-0.70034	0.00683	1.43714	1.25845	2.61630
0.00000	0.70711	0.70711	-0.00996	0.69818	0.70755	4.11327	2.54427	1.10431
0.00000	-0.70711	0.70711	-0.01919	-0.71986	0.72655	1.39109	2.51694	1.20244
0.57735	0.57735	0.57735	0.56993	0.56632	0.56993	3.86936	1.51651	1.35488
-0.57735	-0.57735	-0.57735	-0.57379	-0.57361	-0.55001	1.75912	3.54975	3.80466
-0.70711	0.70711	0.00000	-0.70448	0.70082	0.01305	4.18430	3.77674	2.51585
0.57735	-0.57735	0.57735	0.56134	-0.57896	0.58527	1.63297	1.49879	1.43838
0.00000	-0.70711	-0.70711	0.00615	-0.69112	-0.68832	1.51460	2.53052	4.02233
0.57735	-0.57735	-0.57735	0.58126	-0.56337	-0.57078	1.72977	1.48326	3.74964
0.70711	0.00000	0.70711	0.69232	0.00010	0.70427	2.70636	1.27716	1.13476
0.70711	0.00000	-0.70711	0.71721	0.01425	-0.71055	2.84069	1.25961	3.94639

0.57735	0.57735	-0.57735	0.58954	0.58964	-0.58610	3.96255	1.52115	3.67062
-0.57735	0.57735	0.57735	-0.58489	0.56944	0.59045	3.89374	3.56774	1.35817
0.00000	0.70711	-0.70711	0.01588	0.71714	-0.70667	4.20775	2.51842	3.92350
0.70711	0.70711	0.00000	0.71058	0.71815	-0.01250	4.14756	1.29124	2.51440
-1.00000	0.00000	0.00000	-0.97599	-0.00273	0.02774	2.81063	4.30646	2.56271
0.00000	-1.00000	0.00000	-0.00919	-0.93327	0.02320	0.89276	2.51882	2.64527
-0.57735	-0.57735	0.57735	-0.59323	-0.58874	0.60572	1.65599	3.58287	1.46429
-0.57735	0.57735	-0.57735	-0.56508	0.58142	-0.56529	3.98491	3.55580	3.68745
-0.70711	0.00000	-0.70711	-0.69617	0.00459	-0.68442	2.86116	3.79011	3.99361
0.00000	0.00000	1.00000	-0.01953	-0.01300	0.97973	2.69526	2.54560	0.57646
-0.70711	-0.70711	0.00000	-0.71297	-0.71375	0.03289	1.47076	3.79415	2.59548
0.00000	1.00000	0.00000	0.00533	0.94304	-0.00361	4.70337	2.54046	2.48763
1.00000	0.00000	0.00000	0.97617	0.00197	-0.00903	2.76331	0.76069	2.57403
-0.70711	0.00000	0.70711	-0.72250	-0.01558	0.72970	2.75198	3.80722	1.15592

Data Set 4

0.35355	0.00000	-0.35355	0.37079	0.01998	-0.36729	2.82675	1.89109	3.33737
0.05774	-0.05774	-0.05774	0.06936	-0.04556	-0.06489	2.69053	2.40379	2.72396
-0.10000	0.00000	0.00000	-0.08959	0.01117	-0.00498	2.79368	2.68051	2.60040
-0.28868	0.28868	-0.28868	-0.27062	0.30344	-0.29398	3.40969	3.02859	3.15269
-0.28868	0.28868	0.28868	-0.28148	0.29486	0.28251	3.34779	3.00995	2.00147
0.00000	0.10000	0.00000	0.01068	0.11454	-0.00823	3.00063	2.50899	2.60829
0.00000	0.00000	0.10000	0.00851	0.01825	0.09373	2.78423	2.50283	2.39763
0.07071	0.07071	0.00000	0.08180	0.09023	-0.00897	2.96602	2.36302	2.62934
0.28868	-0.28868	-0.28868	0.30217	-0.26332	-0.29706	2.25942	1.98955	3.22500
0.05774	-0.05774	0.05774	0.06593	-0.03977	0.05024	2.68072	2.40296	2.48875
0.00000	0.21213	0.21213	0.00775	0.22713	0.20285	3.18767	2.50840	2.15391
0.00000	-0.35355	0.35355	0.00148	-0.34069	0.35162	2.08119	2.48871	1.92876
0.70000	0.00000	0.00000	0.71028	0.02121	-0.02001	2.79469	1.25974	2.63602
0.35355	-0.35355	0.00000	0.36143	-0.33524	-0.00791	2.11070	1.87444	2.63319
-0.05774	-0.05774	0.05774	-0.04857	-0.04006	0.05278	2.68591	2.60576	2.48859
0.21213	0.21213	0.00000	0.22369	0.23171	-0.01338	3.21790	2.13002	2.60795
-0.21213	0.00000	0.21213	-0.20522	0.01426	0.20891	2.77513	2.87047	2.16642
-0.17321	0.17321	-0.17321	-0.15906	0.19017	-0.17952	3.16709	2.81914	2.93941
0.07071	0.00000	-0.07071	0.08239	0.01683	-0.07954	2.80808	2.38018	2.75345
0.35355	0.35355	0.00000	0.36629	0.37015	-0.01861	3.48978	1.88474	2.60646
-0.35355	-0.35355	0.00000	-0.34601	-0.34226	0.00426	2.11660	3.15377	2.60959
-0.70000	0.00000	0.00000	-0.68942	0.00922	0.00670	2.80809	3.76687	2.56407
-0.21213	-0.21213	0.00000	-0.20311	-0.19898	0.00019	2.38701	2.88364	2.60873
0.00000	0.00000	-0.50000	0.01952	0.02070	-0.50704	2.85914	2.52316	3.61642
0.00000	0.07071	-0.07071	0.01181	0.08718	-0.07812	2.94197	2.50836	2.74307
-0.21213	0.00000	-0.21213	-0.19743	0.01672	-0.21489	2.81522	2.89146	3.02029
0.00000	0.00000	0.70000	-0.00245	0.00725	0.69392	2.71977	2.50730	1.22121
0.00000	-0.49497	-0.49497	0.01496	-0.47374	-0.49497	1.89914	2.52605	3.63458
-0.30000	0.00000	0.00000	-0.29027	0.01270	-0.00125	2.79579	3.03771	2.59366
0.00000	0.00000	0.30000	0.00464	0.01013	0.29293	2.76697	2.48948	1.99037
0.00000	0.49497	-0.49497	0.02196	0.51207	-0.50905	3.81274	2.52071	3.57172
-0.07071	-0.07071	0.00000	-0.06122	-0.05769	-0.00507	2.66401	2.63064	2.60633
0.40415	-0.40415	-0.40415	0.41812	-0.37979	-0.41427	2.04781	1.78616	3.46167
0.49497	0.00000	-0.49497	0.51401	0.02477	-0.51082	2.83538	1.63639	3.61114
0.30000	0.00000	0.00000	0.31044	0.01705	-0.01287	2.79021	1.98208	2.61679
0.00000	0.30000	0.00000	0.01223	0.31339	-0.01088	3.37987	2.50673	2.58498
0.05774	0.05774	0.05774	0.06610	0.07209	0.04915	2.89613	2.39740	2.47416
-0.05774	0.05774	-0.05774	-0.04480	0.07294	-0.06442	2.91859	2.61179	2.71061
0.00000	-0.35355	-0.35355	0.01396	-0.33408	-0.35595	2.14407	2.49039	3.35931
0.07071	-0.07071	0.00000	0.08055	-0.05718	-0.00705	2.66361	2.37413	2.61773
-0.40415	-0.40415	-0.40415	-0.38961	-0.38676	-0.39871	2.06992	3.23812	3.42826
-0.07071	0.00000	0.07071	-0.06142	0.01476	0.06534	2.78386	2.62446	2.45840
-0.07071	0.00000	-0.07071	-0.05919	0.01338	-0.07656	2.80657	2.61191	2.76427
-0.49497	-0.49497	0.00000	-0.48758	-0.48582	0.00936	1.86494	3.38379	2.61798
-0.21213	0.21213	0.00000	-0.20022	0.22489	-0.00602	3.22229	2.89135	2.58946

0.00000	0.21213	-0.21213	0.01487	0.22898	-0.22243	3.24294	2.51270	3.01680
-0.17321	-0.17321	0.17321	-0.16668	-0.16506	0.17124	2.44178	2.80465	2.26518
0.00000	-0.21213	-0.21213	0.01332	-0.19784	-0.21654	2.40189	2.51322	3.04346
0.21213	-0.21213	0.00000	0.22131	-0.19593	-0.00822	2.37803	2.12733	2.62448
0.00000	0.35355	0.35355	0.00683	0.36341	0.34171	3.45300	2.51104	1.87101
0.00000	0.07071	0.07071	0.00985	0.08142	0.06282	2.92857	2.48329	2.46212
0.00000	0.00000	-0.10000	0.01242	0.01397	-0.10709	2.80240	2.50625	2.80394
-0.50000	0.00000	0.00000	-0.48906	0.00920	0.00207	2.79912	3.39387	2.58016
0.00000	-0.49497	0.49497	-0.00200	-0.48832	0.49466	1.81108	2.48562	1.65716
-0.49497	0.00000	-0.49497	-0.47570	0.01343	-0.49248	2.84261	3.39255	3.58816
0.17321	0.17321	-0.17321	0.18785	0.18837	-0.18494	3.16054	2.20531	2.95367
0.07071	0.00000	0.07071	0.07939	0.00888	0.06335	2.78437	2.37852	2.45827
0.00000	0.49497	0.49497	0.00424	0.50074	0.48089	3.73013	2.50249	1.58714
0.17321	0.17321	0.17321	0.18154	0.18498	0.16079	3.11125	2.19845	2.24777
-0.35355	0.00000	-0.35355	-0.33718	0.01504	-0.35424	2.82762	3.14287	3.30276
0.49497	-0.49497	0.00000	0.50184	-0.48247	-0.00894	1.84384	1.62309	2.65149
-0.35355	0.00000	0.35355	-0.34923	0.00513	0.35325	2.76467	3.12489	1.88797
-0.40415	0.40415	-0.40415	-0.38375	0.41968	-0.40915	3.64072	3.23446	3.37093
0.10000	0.00000	0.00000	0.11004	0.01500	-0.00832	2.80037	2.31690	2.60399
0.00000	-0.07071	-0.07071	0.01037	-0.05762	-0.07653	2.66949	2.50639	2.74958
0.40415	0.40415	-0.40415	0.42471	0.42680	-0.42429	3.62432	1.82334	3.40282
0.00000	0.50000	0.00000	0.01390	0.51364	-0.01401	3.78341	2.52479	2.54811
-0.40415	-0.40415	0.40415	-0.40370	-0.39996	0.41064	1.99812	3.20751	1.82295
0.00000	0.70000	0.00000	0.01537	0.71353	-0.01617	4.14564	2.52427	2.54009
0.35355	0.00000	0.35355	0.35773	0.01153	0.33996	2.75080	1.87914	1.91002
-0.17321	-0.17321	-0.17321	-0.16144	-0.15821	-0.17433	2.48544	2.82500	2.94650
-0.07071	0.07071	0.00000	-0.06008	0.08323	-0.00631	2.93735	2.63114	2.59926
0.00000	-0.07071	0.07071	0.00863	-0.05876	0.06520	2.65691	2.50535	2.46543
0.00000	0.00000	-0.30000	0.01556	0.01658	-0.30689	2.83392	2.51775	3.21710
0.00000	0.00000	0.50000	0.00065	0.00474	0.49356	2.74882	2.49520	1.60496
-0.40415	0.40415	0.40415	-0.39834	0.40778	0.39989	3.57368	3.25511	1.75005
0.28868	0.28868	0.28868	0.29572	0.30054	0.27257	3.34753	1.99050	2.00368
0.40415	-0.40415	0.40415	0.40380	-0.39159	0.39581	1.98516	1.77690	1.83028
0.50000	0.00000	0.00000	0.51066	0.01568	-0.01616	2.78000	1.62142	2.61694
0.00000	-0.50000	0.00000	0.00689	-0.48678	0.00001	1.84592	2.50230	2.64320
0.21213	0.00000	-0.21213	0.22590	0.01974	-0.22306	2.81505	2.14211	3.04900
0.21213	0.00000	0.21213	0.21898	0.01429	0.20153	2.76651	2.13221	2.17697
-0.49497	0.00000	0.49497	-0.49273	0.00835	0.49718	2.76584	3.38266	1.61775
0.00000	-0.10000	0.00000	0.00945	-0.08650	-0.00477	2.59939	2.50301	2.60912
0.17321	-0.17321	-0.17321	0.18456	-0.15521	-0.18069	2.47153	2.20601	2.97153
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Data Set 5

0.35355	0.00000	-0.35355	0.35779	0.00483	-0.34957	2.81449	1.90719	3.28688
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